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AHEAD2020 – WP11.4: report on radiation testing of THESEUS/XGIS detecting elements, FEE ASIC and electronic components (deliverable D71)

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Introduction

Even though at the end (June 2021) ESA selected a mission to Venus (EnVision) as final M5 mission candidate, the Phase-A study of THESEUS as candidate ESA/M5 mission was very successful, demonstrating the technical and programmatic feasibility of the mission and of the scientific instruments (specifically, the XGIS), as well as the excellence of the scientific objectives and expected performances.

Since July 2021, the THESEUS Consortium is working hardly for fully exploiting the great heritage of the three years Phase-A study, in view of further development of the instruments and providing new opportunities for the mission as a whole. These include responding to the new ESA Call, issued in December 2021, for next M-class mission to be launched in 2037, establishing collaborations with other similar space projects like the US-led Gamow explorer (proposal for NASA/MIDEX), working on small mission concepts based only, or mostly, e.g. on a re-configured XGIS instrument. In particular, the high TRL level (4-5 for ASIC and SDD+CsI detectors, 5-6 for detection plane module, 8-9 for the imaging system), the modularity of the design and its unprecedented combination of effective area, wide energy band, timing resolution and FoV make the XGIS an ideal instrument for inclusion in the payload of missions of any size (from medium large to small to cubesats) totally or partly dedicated to the investigation and full exploitation of GRBs.

The irradiation tests of electronic components of BEE and PSU boards, of detecting elements and of FEE ASICs here reported were performed with the aim of further improving the TRL of XGIS detectors and fully exploit the similarities and synergy with the detection system being developed for the HERMES project (also supported by AHEAD2020).

Simulations aimed at optimizing the XGIS detection plane design for source localization and polarization measurements are also on-going.

Tests on XGIS electronic components

Since THESEUS will be launched in a low-Earth orbit, it will be subject to a large amount of high-energy radiation fluxes (mostly cosmic-rays and geomagnetically trapped protons). This hazardous space environment is usually problematic for the use of electronic components, since ionization streaks produced by the interaction of the high energy particles with the electronic itself can give rise to several issues, beside the total ionizing dose effects, called Single Event Effects (SEE). These can be either destructive (e.g., latch-ups) or non-destructive (e.g., bit-flips or upsets).

For the XGIS instrument design, however, special care will be used to select components that are expected to be tolerant with respect to the foreseen in-orbit environment. However, for a few individual components included in the HERMES BEE and PSU boards (and likely foreseen also for XGIS) there is no radiation-related information available on the component datasheet or on the relevant literature (such as the Radiation Effects Data Workshop proceedings).

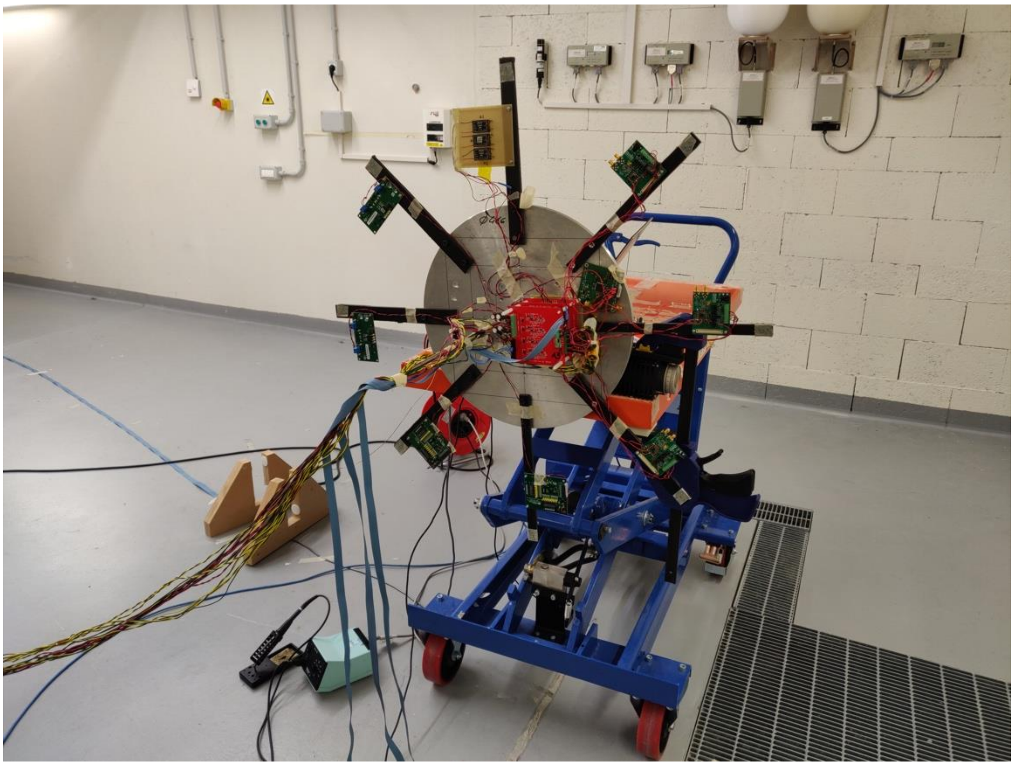
Usually, electronic components are tested for SEEs using heavy ion beams. However, this kind of testing is usually cumbersome (requiring special custom-made boards for testing single components in isolation, use of vacuum, need of decapsulation of packaged elements, etc.). However, a proton beam allows to test the components already integrated on their “final” or on commercial PCBs, and standard literature results (see e.g., Petersen 1998 IEEE Trans. Nucl. Sci., 45,6; Barak 2006 IEEE Trans. Nucl. Sci. 53,6) allow to compare the results of a proton irradiation with those of a heavy-ion beam irradiation. Moreover, it allows simultaneously to test for total dose effects.

The proton irradiation campaign took place at the Trento Protontherapy Center (Trento, Italy) on October 14-15, 2020.

The following table summarizes the electronic components tested. Among them, a high-voltage converter (for generating the SDD bias voltage from the 12 V satellite bus line) and analog-to-digital converters for housekeeping values.

Component	Model	Mounted on	Board model
DC-DC converter	Pico 12SAR250	Custom board (3 DUTs/board)	N/A (custom)
ADC	Analog Devices ADAQ7980	Evaluation board (3 boards)	EVAL-ADAQ7980SDZ
ADC	Maxim Integrated MAX11643	Evaluation board (2 boards)	MAX11633EVSYS
DC-DC converter	Texas Instruments LMZ30602	Evaluation board (2 boards)	LMZ30602EVM-002

Each electronic component was mounted on a rotating wheel and irradiated one at time. The behavior of each board was monitored by a custom-made board ("Multi-OCP").



The wheel with the eight test boards mounted on the experimental room. The Pico board (slot 1) is the uppermost, while the others are numbered clockwise. The stack of red PCBs near the wheel axis is composed by the Multi-OCP control boards, while the small board between slots 2 and 3 generates the clock and convert signals for the ADAQ7980 boards.

For the irradiation campaign, the accelerator beam energy as fixed at 148 MeV, implying an energy at the target of about 140 MeV, i.e., well within the saturation cross-section range. The beam spot is therefore sufficiently large to illuminate uniformly all the devices under test

At 140 MeV, approximately 1.36×10^{7} protons/cm^{2} are required to deliver a total ionizing dose of 1 rad on a Silicon target.

The following table shows the irradiation log.

DUT	Start date/time	Total dose	Machine parameters	Notes
Pico 12SAR250	2020-10-14, 20:25	0.97×10^{11} p/cm^{2} (~7.1 krad)	200 nA, 140 MeV, 14'	One of the three DUTs experienced a hard latch-up failure at a dose of ~6.2 krad.
ADAQ7980 #2	2020-10-14, 21:11	0.69×10^{11} p/cm^{2} (~5.1 krad)	200 nA, 140 MeV, 10'	No latch-ups.
ADAQ7980 #1	2020-10-14, 21:34	0.69×10^{11} p/cm^{2} (~5.1 krad)	200 nA, 140 MeV, 10'	No latch-ups.

ADAQ7980 #3	2020-10-14, 21:57	0.69×10^{11} p/cm^2 (~5.1 krad)	200 nA, 140 MeV, 10’	No latch-ups.
MAX11633 #1	2020-10-15, 21:53	1.03×10^{11} p/cm^2 (~7.6 krad)	200 nA, 140 MeV, 15’	No latch-ups.
MAX11633 #2	2020-10-15, 22:23	1.03×10^{11} p/cm^2 (~7.6 krad)	200 nA, 140 MeV, 15’	No latch-ups.
LMZ30602 #3	2020-10-15, 22:51	1.03×10^{11} p/cm^2 (~7.6 krad)	200 nA, 140 MeV, 15’	No latch-ups.

The first irradiation campaign was a success, with only one device (one of the three Pico 12SAR250 DC-DC converters) experiencing a failure or latch-up.

Tests on XGIS scintillator crystals

The scintillator selected for use on HERMES, and under study for THESEUS, is GAGG:Ce ($Gd_3Al_2Ga_3O_{12}$:Ce, Cerium-doped Gadolinium Aluminum Gallium Garnet). It is a promising scintillation crystal displaying a wide array of appealing features for space applications: very high light-yield, fast-decay times, very low intrinsic background, and mechanical robustness.

However, GAGG:Ce is still a recently developed scintillator, and, as a consequence, literature is lacking on points crucial to its applicability in space. For example, GAGG:Ce is characterized by unusually intense and long-lasting afterglow emission, a slow phosphorescence component in scintillation light. Afterglow emission is a source of background noise and is induced by the exposure of GAGG:Ce crystals to electromagnetic and particle radiation.

To tackle this last concern an irradiation campaign was conducted at Trento Proton Therapy Center (TPTC) in which a GAGG:Ce sample was irradiated with 70 MeV protons. The choice of particle specie, energy and fluences was driven by the need to simulate the nature of the radiation environment of near-equatorial LEO orbits and the constraints of the cyclotron particle accelerator available at TPTC.

From the irradiation results, and from their modelling, discussed in depth in the paper **Dilillo et al. (2022) NIM B 513, 33**, the conclusion that GAGG:Ce afterglow emission should not endanger operations in low-Earth orbit.

Tests on XGIS front-end ASICs

The ORION ASIC is the foreseen front-end electronics to be interfaced with the THESEUS/XGIS SDDs. Such a device must be able to withstand the effects of the harsh orbital environment around the Earth, both in form of cumulative and transient effects. In fact, the ionization tracks left behind by heavy ions through the sensitive layers of the device may cause the onset of sudden current spikes, whose effects may vary from reversible bit flips (Single Event Upsets or SEUs) to potentially catastrophic failure (Single Event Latch-ups or SELs). Furthermore, charges generated by high-energy particles and photons may get trapped in the surface oxide layers (Total Ionising Dose or TID) and, over time, degrade the spectroscopic performances of the ASIC.

The RIGEL ASIC is fabricated using the same AMS 0.35 µm CMOS technology used for ORION and shares a similar architecture in various components of the electronic chain (such as the preamplifier and the shaper stages). The AMS technology was selected due to its consolidated noise performance in spectroscopy-grade applications. The RIGEL is a two-dimensional mixed-signal multi-channel ASIC de- signed to be bump-bonded to a multi-pixel silicon detector to carry out spectral-timing (and imaging) studies.

Experimental testing was carried out in November 2021 at the RADiation Effects Facility of the University of Jyväskylä (Finland).

The campaign aimed at studying the response of the ASIC to radiation damage, in the form of both Total Ionizing Dose and Single Event Effects, especially latch-ups and bit upsets. Experimental results, discussed in the paper **Ceraudo et al. (2022) NIM A 1037, 166903**, were then combined with simulations of the space environment for a low-inclination equatorial orbit and for a Sun-synchronous orbit. The analysis shows that the device under study, and therefore the ORION ASIC, may be safely operated on an equatorial orbit without any circuitry to protect it from transient radiation phenomena, whereas the need of such a precaution is necessary in the case of a Sun-synchronous orbit.

Annexes:

- article Dilillo et al. (2022) NIM B 513, 33
- article Ceraudo et al. (2022) NIM A 1037, 166903